

QCD AGAINST BLACK HOLES* ?

Ilya I. Royzen

P.N. Lebedev Physical Institute of RAS
e-mail: <royzen@lpi.ru >

Abstract

Along with compacting baryon (neutron) spacing, two very important factors come into play at once: the lack of self-stabilization within a compact neutron star (NS) associated with possible black hole (BH) horizon appearance and the phase transition - color deconfinement and QCD-vacuum reconstruction - within the nuclear matter. That is why both phenomena should be taken into account side by side, as the gravitational collapse is considered. Since, under the above transition, the hadronic-phase vacuum (filled up with gluon and chiral $q\bar{q}$ -condensates) turns into the "empty" (perturbation) subhadronic-phase one and, thus, the corresponding (very high) pressure falls down rather abruptly, the formerly cold (degenerated) nuclear medium starts to implode into the new vacuum. If the mass of a star is sufficiently large, then this implosion produces an enormous heating, which stops only after quark-gluon plasma of a temperature about 100 MeV (or even higher) is formed to withstand the gravitational compression (whereas the highest temperatures of supernovae bursts are, at least, one order lower). As a consequence, a "burning wall" must be, most probably, erected on the way of further collapsing the matter towards a black hole formation.

*Talk at the 4th International Sakharov Conference, Moscow, May 18-23, 2009.

1 Twofold signal of neutron star instability

Two mechanisms underlying the neutron star instability are to be discussed below: the first one consists in hadronic phase \longrightarrow subhadronic phase (HPh \rightarrow SHPh) transition within nuclear matter (it is described here in more detail) and the second one, which is rather familiar, is shutting to BH. They are engaged in "competition" with each other, however they make the star to evolve in absolutely alternative ways; thus, the main point is to understand, which one comes before into operation ¹.

1.1 Phase transition in nuclear medium

Schematically, this transition is depicted as follows:

$$\begin{array}{ccc}
 \text{QCD HPh} & \Longleftrightarrow & \text{QCD SHPh} \\
 \Downarrow & & \Downarrow \\
 P_{vac}^0 = -\varepsilon_{vac}^0 \simeq \varepsilon_n \simeq 5 \cdot 10^{-3} \text{ GeV}^4 & \Longleftrightarrow & P_{vac} = -\varepsilon_{vac} \rightarrow 0 \\
 \Downarrow & & \Downarrow \\
 P_{tot} \simeq P_{vac}^0 [\text{rarefied gas of hadrons}] & \Longleftrightarrow & P_{tot} = P_{vac} + P_{part}
 \end{array}$$

Here $(\varepsilon_{vac}^0, P_{vac}^0)$ and $(\varepsilon_{vac}, P_{vac})$ stand for the vacuum (energy, pressure) in HPh and SHPh, respectively, while P_{part} is the pressure of particles and P_{tot} is the overall pressure within the nuclear medium.

One has to consider two conceivable scenarios of this phase transition [1, 2, 3] - the hard scenario, when the HPh transforms at some density (pressure) directly (stepwise) into the current quark state (this is a "conventional" phase transition), and the soft one, which admits an intermediate state in between. This state is attributed with deconfined dynamical quarks (valons) - quazi-particles of non-fixed mass, which diminishes along with the density (pressure) increase. It is shown below that both scenarios result in developing strong instability under the phase transformation.

¹Here the non-rotating objects are under discussion only. Allowing for rotation would undoubtedly lead to the enhancement of instability

1. *Hard (stepwise) scenario* : SHPh is just $P_{vac} = \varepsilon_{vac} \equiv 0$

This implies that the chiral symmetry restores and the current quarks - almost massless (u, d)- and ~ 150 -MeV s -ones - are emerged promptly, as neutrons crush down. It is illustrated in Fig.1 [1] that transition into degenerate ("cold") quark gas is ruled out: this scenario should unavoidably result in immediate development of a collapse into the new ("empty") vacuum and, thus, in an enormous heating ² (see an estimate below) of the nuclear medium at the phase transition point.

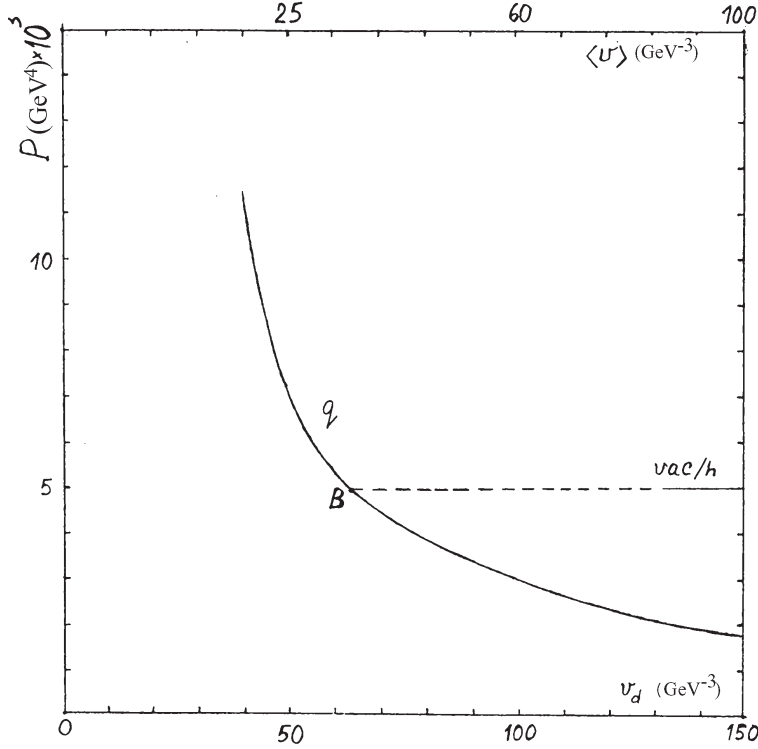


Figure 1: The pressure of non-perturbation QCD vacuum condensate in the HPh (horizontal segment vac/h) vs the pressure of degenerate ("cold") perfect gas of (u, d, s) current quarks (curve q). As the particle density approaches the critical value (neutron spacing becomes compact, particle specific volume is $\langle v \rangle \simeq 100 \text{ GeV}^{-3}$), the occurrence of a giant gap between the HPh- and SHPh-phase pressures is quite well pronounced - the former is about three times as large as the latter one.

²Two pressures - HPh-vacuum and SHPh-particle ones - become equal only when the particle number density is 3-4 times higher (point B in Fig.1). It is worth noting that the neutrinos get stuck under relevant densities and, thus, there is no way for an "instant" energy release.

2. *Soft scenario:* No stepwise HPh \longleftrightarrow SHPh transition (crossover)

In other words, as the neutrons "get in touch with each other" and lose their identity, the degrees of freedom which come into life are associated with some hypothetical quasi-particles - massive dynamical quarks (valons) [4, 5, 6, 7, 8]: they become the first color objects to be unleashed (color deconfinement); then, both the valon masses and vacuum condensate pressure decrease along with the particle density increase [2]; finally, the valons turn into the current quarks and the chiral symmetry restores. Thus, $P_{vac} = -\varepsilon_{vac} \rightarrow 0$ more or less gradually.

A reasonable approach [2], which describes the degenerate valonic gas at particle energy densities $\varepsilon \geq |\varepsilon_{vac}^0|$, is based on the EoS:

$$\varepsilon = \frac{6N_f}{2\pi^2} \int_0^{p_F} dp p^2 \sqrt{p^2 + m^2(\varepsilon)}, \quad (1)$$

where $N_f = 3$ is the number of flavors allowed for, the Fermi momentum $p_F = (\frac{\pi^2}{N_f \langle v \rangle})^{1/3}$, and closely interrelated with each other vacuum current energy density and valonic masses are taken as follows:

$$\varepsilon_{vac} \equiv -P_{vac} \simeq \varepsilon_{vac}^0 \exp[-a(\varepsilon/|\varepsilon_{vac}^0| - 1)] \quad (2)$$

and

$$m_{u,d} \simeq m_0 \exp[-a(\varepsilon/|\varepsilon_{vac}^0| - 1)], \quad (3)$$

where $m_0 \simeq \frac{1}{3}m_n \simeq 330 \text{ MeV}$ ³ and $a \sim 1$ or larger is a free parameter, which describes the rate of QCD vacuum condensate destruction. The numerical solution of eq.(1), supplemented with eq's.(2,3) is presented in Fig.2. Note, that only values $a \geq 1$ are physically reasonable because the HPh vacuum condensate should be crucially affected by the particle energy density, as the latter one approaches the absolute value of the condensate strength itself (or even earlier). Below, in Fig.2, the curves 2-4, which refer to $a < 1$, are depicted for an illustration only. It is evident that hard scenario comes back in the limit $a \rightarrow \infty$.

³Actually, the numerical solution of eq.(1) allowed for the $\sim 150\text{-MeV}$ mass difference between (u, d) - and s -valons, but no significant correction was shown to come therefrom [2].

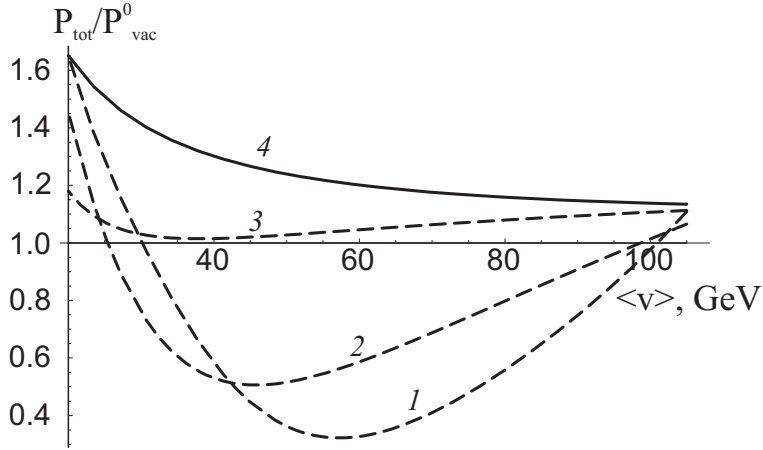


Figure 2: The soft-scenario total pressure within the SHPh-medium, $P_{tot} = P_{vac} + P_{part}$, as a function of particle specific volume $\langle v \rangle$ at $\langle v \rangle \leq 100 \text{ GeV}^{-3}$, if the nuclear matter were "cold" (curves 1,2,3,4 refer to $a = 1, 0.5, 0.1, 0.01$, respectively). It is evident that no "cold" steady state of a star with quark center is accessible at $a \geq 0.1$, since the inequality $dP_{tot}/d\langle v \rangle > 0$ signaling of instability holds within some density interval to be passed along that way.

Thus, we come to to the principally significant conclusion, that *no way exists for preserving degeneracy under $HPh \longrightarrow SHPh$ phase transition*.

Does it rule out the possibility of BH formation in course of a compact star evolution?

We try to put forward some seemingly weighty arguments that, indeed, it does.

1.2 NS vs BH

1. The upper bound for NS

As being emerged, the central domain of SHPh starts swelling until a balance is established between further heating due to gravitational compression and energy outflow. If the equilibrium SHPh mass is sufficiently large for making the real high-temperature quark-gluon plasma (QGP - nearly perfect gas of multiply produced quarks and $q\bar{q}$ -pairs, baryonic chemical potential thus becoming about zero) and yet is small as compared to the total star mass, then a reasonable (although elementary and crude) condition for the hydrodynamic (fast process) equilibrium reads:

$$\begin{aligned} \frac{\pi^2}{30}(2 \times 8 + 2 \times 3 \times 2 \times 3 \times \frac{7}{8}) T^4 &\simeq \\ \frac{6}{7} G (\varepsilon_n + 3P_n + 2|\varepsilon_{vac}^0|)^2 V/R &\simeq \frac{4\pi}{3} \frac{6}{7} (3 \div 4)^2 G \varepsilon_n^2 R^2, \end{aligned} \quad (4)$$

where the mean energy density of QGP at the star central interior (the left-hand side) is equated to that of HPh non-relativistic star main body. Here T is the QGP temperature, G is the gravitational constant, R and V stand for the star radius and volume, respectively. Also the "weigh of pressure" is taken into account, what is especially significant for the HPh vacuum: $\varepsilon_{vac}^0 + 3P_{vac}^0 = 2|\varepsilon_{vac}^0| \simeq 2\varepsilon_n$. After insertion in eq.(4) the proper numerical values, one obtains

$$T \simeq (170 - 200) \sqrt{k} \text{ (MeV)}, \quad (5)$$

where $k = R/10 \text{ km}$. Since, according to the well known lattice simulations [9], QGP is expected to come into being just at $T \simeq (170 - 200) \text{ MeV}$, the hydrodynamic equilibrium between the first appeared hot SHPh at the star interior and cold HPh at its periphery could be maintained at $R \simeq 10 \text{ km}$ and corresponding ("critical") star mass $M_{NS} \simeq 2.3 M_{\odot}$ ⁴, *but this equilibrium is achieved at the price of an enormous thermodynamic (slow process) disbalance* (note again that neutrinos get stuck at the relevant densities of nuclear matter). Thus, at $M_{NS} \geq 2.3 M_{\odot}$, the thermal instability grows up resulting in heat outflow, which gets more and more powerful along with M_{NS} increase

⁴ This estimate is in quite good agreement with the large body of data on the NS masses.

and, hence, produces eruption of mass and energy which should result in the following observable phenomena:

- either in the successive GRB's (the more destructive ones the larger is M_{NS} , up to being $(10^4 - 10^5)$ times as powerful as those emerged under the typical supernovae explosions, because the relevant temperatures differ by more then one order), which stop as M_{NS} grows down to become below the critical value, $M_{NS} \simeq 2.3 M_{\odot}$, since then no QGP forms at the star center;
- or in the total self-destruction of the star.

However, still one way of star evolution is conceivable:

- *BH may shut to and trap the matter before the above mechanisms come into play*

2. The lower bounds for BH rule it out ?

The elementary condition for horizon first appearance within the body of a compact star reads: $\frac{2GM_g}{R_g} = 1$, or

$$R_g \simeq \left[\frac{3}{8\pi G \langle \varepsilon_g \rangle} \right]^{1/2}, \quad (6)$$

where R_g and $\langle \varepsilon_g \rangle$ are the BH radius and its mean energy density, respectively. For getting the lower estimate of R_g , one has to take into account that $\langle \varepsilon_g \rangle \leq \varepsilon_n$ because the energy density profile maximizes at the star center but should, nevertheless, not exceed the value ε_n there (to escape the premature phase transition instability there and all the cataclysms what follow, see above). Thus, we obtain from eq.(6)

$$R_g \geq 12 \text{ km and } M_g \geq 4 M_{\odot}$$

and, therefore, *the strong NS instability (at $M_{NS} \geq 2.3 M_{\odot}$, see above) is expected to develop well before BH appearance.*

One can by no means diminish the above BH parameters even allowing for powerful confluent shock waves caused by preceding supernovae explosion, because any attempt of such a kind would ask unavoidably for $\langle \varepsilon \rangle \geq \varepsilon_n$ inside the wave body itself, what,

in turn, would result in the immediate developing of the aforementioned $\text{HPh} \rightarrow \text{SPh}$ phase transition instability, enormous heating and, finally, in rupturing the shock wave body from within.

2 Conclusion

Two QCD-motivated "alarming" signals are put forward:

- neutron stars of highest masses are in face of instability associated with QCD-vacuum transformation under $\text{HPh} \rightarrow \text{SPh}$ transition;
- this instability makes rather problematic the accessibility of a black hole configuration as the final state of collapsing compact star;

- It is difficult to resist the temptation of linking the instability under discussion and the poorly understood data on very distant (young) GRB's of highest energy, like GRB 090423 [10], GRB 080916C [11], GRB 080319B ("naked eye") [12], etc.

The work is supported by RFBR, grant #08-02-13637, and by RF President Foundation for The Leading Scientific Schools, grant #NSH-438.2008.2.

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